

## **Modeling Tools for Predicting the Impact of Rolling Resistance on Energy Usage and Fuel Efficiency for Realistic Driving Cycles**

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### **ABSTRACT**

Currently, in the United States there is a growing gap between domestic oil production and consumption. The Department of Energy has developed a modeling tool (known as VISION) that projects future consumption by the transportation sector through the year 2050. This paper uses the VISION model to show that an energy savings of 3.8 billion gallons per year can be achieved with a 2.5% improvement in fleet fuel economy, and proposes that this improvement can be made through lower rolling resistance tires and improved tire pressure maintenance.

Additionally, the National Renewable Energy Lab has developed a vehicle systems analysis tool known as Advanced Vehicle Simulator (ADVISOR) that models vehicle performance over any predefined driving cycle. In this paper ADVISOR is used to compute the effect of rolling resistance on fuel efficiency for two classes of vehicles (passenger car and sport utility vehicle) and several realistic driving cycles (city, highway, aggressive driving). ADVISOR is used to compute the dynamic vehicle forces, fuel economy, and emissions for the various combinations of vehicles, cycles and tire rolling resistance. Using industry-supplied tire rolling resistance data, the ADVISOR simulations showed fuel economy between 2% and 6.5% lower for a light duty passenger car equipped with low rolling resistance tires, and between 1.0% and 3.4% for a sport utility vehicle over the three different drive cycles.

### **INTRODUCTION**

Currently, in the United States, approximately 96% of energy expended for on-road transportation is derived from petroleum. On a given day in the US we consume 10 million barrels of oil for highway transportation by light- and heavy-duty vehicles. The US oil consumption currently accounts for over 40% of the total world transportation energy usage<sup>1</sup>. Tire designs play a critical role in transportation energy use, because a portion of the energy used to propel a vehicle is needed to overcome the rolling resistance of tires. The Department of Energy (DOE) has an array of programs designed to assist in the development of transportation technologies that reduce the United States dependence on imported oil.

The DOE's Office of Transportation Technologies has developed a spreadsheet modeling tool (known as VISION) that projects transportation energy use through the year 2050 for various consumption scenarios<sup>2</sup>. This is one of the tools used by the DOE to analyze various fuel and transportation technology impacts and provide input into program funding decisions.

The National Renewable Energy Lab's (NREL) Advanced Vehicle Simulator, or ADVISOR, was developed for the DOE to assist with the analysis of advanced vehicle systems and help the DOE develop technical targets for new vehicle technologies. ADVISOR provides fast and accurate simulations of both conventional and advanced vehicle configurations. Output from the ADVISOR model provides detailed vehicle system data including power requirements of various components, and in particular power requirements to overcome rolling resistance, aerodynamic drag, and inertia. The tool was first developed in November 1994. Since that time, there have been seven major upgrades leading to the release of ADVISOR 2002 in April of 2002. Over 6000 users from over 70 countries have downloaded the program from the ADVISOR web site (<http://www.ctts.nrel.gov/analysis/advisor.html>).

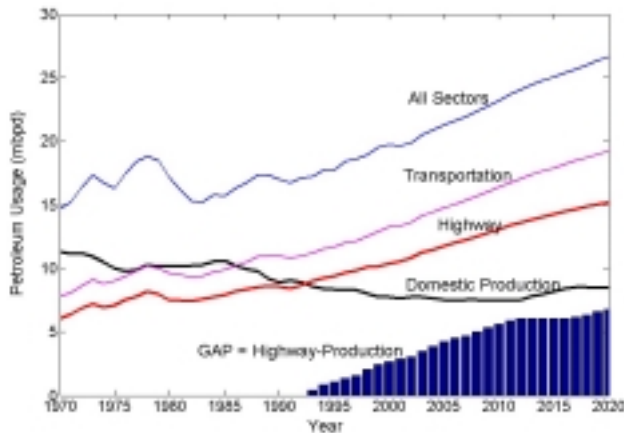
### **NATIONAL VEHICULAR ENERGY USE**

One of the most pressing issues facing the United States and perhaps the world is the question of continued availability of petroleum to fuel our transportation requirements. In the United States, domestic production of petroleum has been on the decline since the 1980's while consumption for transportation continues to increase. The Department of Energy's Energy Information Agency (EIA) provided the following statistics for the year 2000<sup>1</sup>:

- US oil consumption for transportation was 150% of US domestic production.
- Transportation accounted for 68% of US oil consumption.
- The US produced 8.6% of the world's oil, but consumed 26%.

Figure 1 shows the existing and projected gap between US oil production and consumption for transportation.

Included on the graph are US domestic oil production, and consumption by highway, total transportation, and total (all sector) oil consumption. By the year 2000, the gap between domestic production and highway consumption had reached 2.7 million barrels per day (mbpd). Projections by the EIA indicate that this gap could likely go as high as 6.7 mbpd by 2020 as the number of vehicle miles traveled in that time period continues to increase.



**Figure 1. Gap between US Oil Production and Consumption**

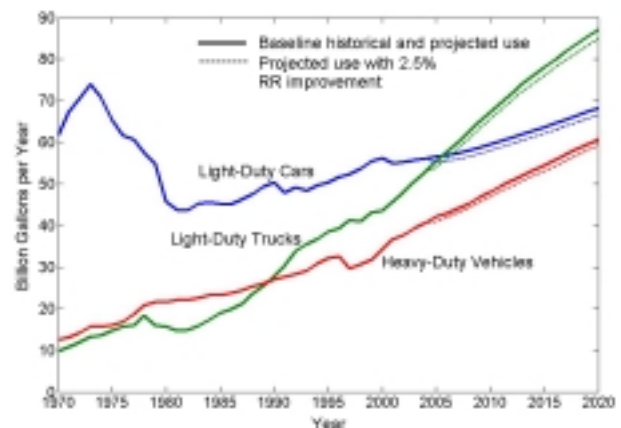
Table 1 shows the US transportation oil demand in the year 2000 and projected to the year 2050<sup>2</sup>. This projection shows the US oil consumption for transportation increasing by a factor of 2.3 over the next 50 years. However, worldwide transportation consumption is projected to increase by a factor of 5.7 in the same time period. Under this scenario the US share of highway vehicle oil consumption is expected to decrease from 42% in 2000 to 17% in 2050 as developing nations increase vehicle ownership.

**Table 1. US and World Oil Demand**

	<b>Oil Demand (mbpd)</b>	
	2000	2050 projection
<b>United States</b>	<b>19</b>	<b>44</b>
Transportation	13	30
Light Vehicles	8	16
Heavy Vehicles	2	5
<b>World</b>	<b>75</b>	<b>186</b>
Transportation	30	170
Light Vehicles	16	77
Heavy Vehicles	8	50
<b>Ratio (US/World)</b>		
Light Vehicles	50%	21%
Light + Heavy	42%	17%

For passenger cars, approximately 4% of the energy consumed is used to overcome tire rolling resistance. In a recent report, the Natural Resources Defense Council (NRDC) concluded that the United States could save approximately 100 million barrels (3.8 billion gallons) of oil per year by improving the rolling resistance of replacement market tires in the light duty fleet by 20%<sup>3</sup>. Additionally, the National Highway Traffic Safety Administration recently reported that 27% of light-duty passenger cars and 30% of light-duty trucks are driven with one or more substantially under-inflated (> 8 psi) tires<sup>4</sup>. Similar, studies have estimated that up to 30% heavy-vehicle trailer tires and 15% of tractor drive axel tires are under-inflated<sup>5</sup>. For light-duty vehicles, it is estimated that 5 psi of under-inflation will reduce vehicle fuel economy by approximately 1%<sup>6</sup>.

For this paper, the DOE's VISION model was used to show the impact of improving vehicle fuel economy by 2.5% through a combined approach of improving tire rolling resistance and better control of tire pressure. Note that the 2.5% improvement in fuel economy is based on the ability to achieve a 20% improvement in rolling resistance with a return factor (the ratio of percent improvement in fuel economy to percent improvement in rolling resistance<sup>6</sup>) of 1.5. Figure 2 summarizes the results of this analysis. The VISION model includes historical fuel consumption data beginning in 1970 and projects US highway fuel consumption beyond 2000 by relating vehicle miles traveled to projections of US population and growth in annual gross domestic product. The model includes data and projections for several different classes of vehicles including light-duty cars, light-duty trucks (including pick-ups, vans, and sport utility vehicles), and heavy-vehicles (class 3 through 8). For each of these vehicle types, the DOE base case assumptions are shown along with the impact of a 2.5% improvement in fuel economy. The gap shown for each vehicle class beginning in 2005 represents the oil savings. Note that for this analysis and the NRDC report the simplifying assumption is made that 100 percent of a barrel of oil is converted to gasoline.



**Figure 2. Impact of Improved Fuel Economy on Reducing Oil Consumption**

This analysis shows a total savings of 3.8 billion gallons per year beginning in 2005 that grows to 5.3 billion gallons per year in 2020 as vehicle miles traveled increases. The total accumulated savings over this time period would be 72 billion gallons of oil. Since the overall consumption is so great the savings potential can appear to be small. However, the savings is significant because it represents an opportunity to impact fuel use in the existing fleet of vehicles. Much of the research in alternative fuels and efficient vehicles such as hybrid electric or fuel cell vehicles could take 20 to 30 years to achieve significant market penetration<sup>2</sup>. For example, to get the same energy savings (3.8 billion gallons per year) from hybrid electric vehicles, we would have to replace 15.7 million average cars (getting 27 mpg and driving 15000 miles per year) with Toyota Priuses (48 mpg). In the long-term it appears that the highly efficient vehicles will be needed, but improvements such as low rolling resistance tires and improved tire pressure maintenance can play a significant near-term role in national energy savings.

## VEHICLE MODELING

ADVISOR is a vehicle simulation tool developed for the DOE to provide quick analysis of the performance and fuel economy of any vehicle type including conventional, electric, fuel cell, and hybrid vehicles. It is very easy to use, and because it is modular and the source code is provided, its component models can be extended and improved quite easily. A more detail description of the model was published in the Journal of Power Sources<sup>7</sup> and the software can be downloaded for free from the web at <http://www.ctts.nrel.gov/analysis>. The ADVISOR model has been validated through vehicle testing at NREL and also independently by several industry users.

ADVISOR's user interface is divided into three graphical user interface (GUI) screens (shown in figures 3,4,5). First the user selects a vehicle from the library of over 30 pre-defined vehicles, including conventional, hybrid, electric, and fuel cell vehicles, and light-duty sedans, sport utilities, trucks and buses. Alternatively the user can set-up their own vehicle or modify one of the existing vehicles. Once the vehicle is defined the user moves to the Simulation Setup screen where they select the driving cycle and/or test procedure that they wish to simulate. ADVISOR has over 50 different driving cycles in its library and several standard test procedures such as the Environmental Protection Agency's city and highway fuel economy and emissions tests, as well as speed and grade performance tests. On a reasonably fast computer (500 MHz) simulations usually take less than one minute to run. The Results screen provides the user with overall driving cycle results such as fuel economy, emissions, acceleration times, and energy usage by the different driveline components. It also provides access to continuous plots of over 100 different parameters related to the engine, transmission, wheel, battery, motor, exhaust, and other component

performance. Additionally, all the input and output variables used in the simulation are available in the Matlab® workspace.



Figure 3. Vehicle Input Screen

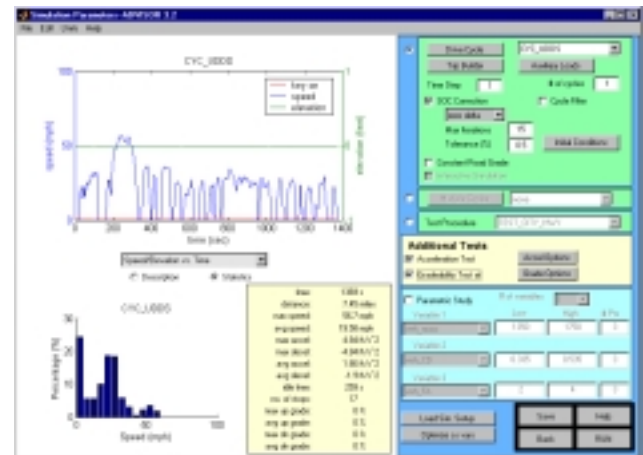


Figure 4. Simulation Setup Screen

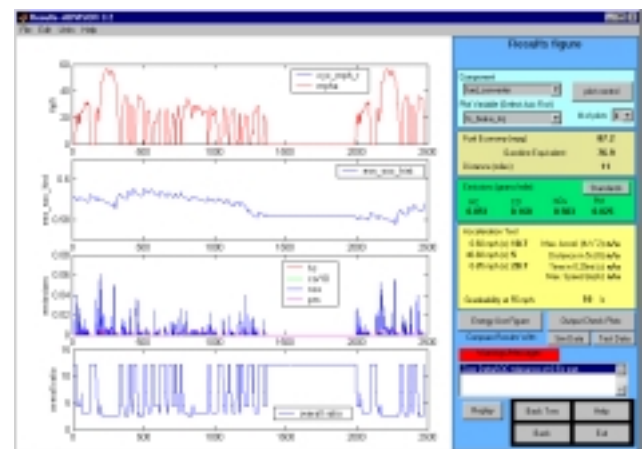


Figure 5. Results Screen

In April of 2002, NREL released ADVISOR 2002. In this latest release, an updated rolling resistance model was included along with related tire rolling resistance test data based on the SAE J2452 test procedures. Previous to the ADVISOR 2002 release, the road-load force due to rolling resistance was calculated as:

$$F_r = C_r \times m \times g$$

Where:  $C_r$  is the rolling resistance coefficient  
 $m$  is the vehicle mass  
 $g$  is the gravitational constant.

Note that this simplified rolling resistance force is not dependent on vehicle speed and does not account for changes in tire pressure.

The improved rolling resistance model included in ADVISOR 2002 is based on the following equation:

$$F_r = P^\alpha L^\beta (a + bV + cV^2)$$

Where:

$P$  is the tire pressure in MPa  
 $L$  is the tire load in kg  
 $V$  is the vehicle speed in m/s  
 $\alpha$ ,  $\beta$ ,  $a$ ,  $b$ , and  $c$  are coefficients used to fit the experimental rolling resistance data

This calculation is incorporated in the rolling resistance portion of the vehicle block diagram shown in the Appendix. For this paper, several simulations were run to show the effect of rolling resistance on fuel economy for a mid-sized sedan and sport utility vehicle tested on three different driving cycles. The cycles selected included the EPA's Federal Test Procedure (FTP) for urban driving, the Highway Fuel Economy Test (HWFET), and the US06 driving cycle used for measuring emissions on an aggressive driving cycle.

Comparisons of the rolling resistance force predicted by the simplified and updated models are shown for the HWFET, FTP, and US06 driving cycles in Figure 6, 7 and 8. The figures show how  $F_r$  in the updated model changes with vehicle speed for three sets of tire data (LO RR, MED RR, and HI RR). The rolling force predicted by the previous ADVISOR model is shown as " $F_r$  for constant RR". The constant  $F_r$  in the simplified model is 141.7 N, which is similar to the  $F_r$  for the medium RR tire on the HWFET. However, the  $F_r$  for the medium RR tire varies from 103.8 N (at very low speeds) to 160.9 N at 80.3 mph during the US06 cycle. The average of non-zero  $F_r$  values was 135.2 N for the HWFET, 119.5 N for the FTP, and 138.0 N for the US06.

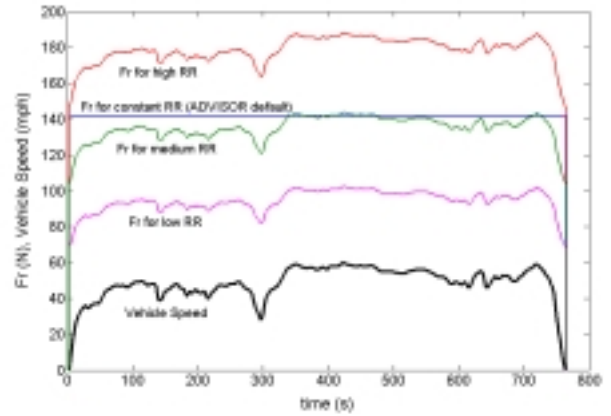


Figure 6. Rolling Force  $F_r$  for HWFET cycle

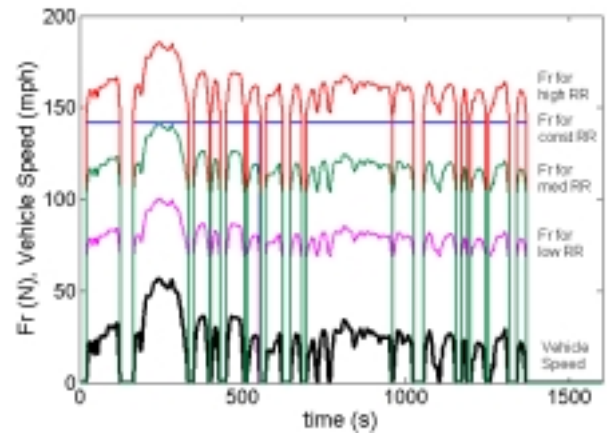


Figure 7. Rolling Force  $F_r$  for FTP cycle Rolling

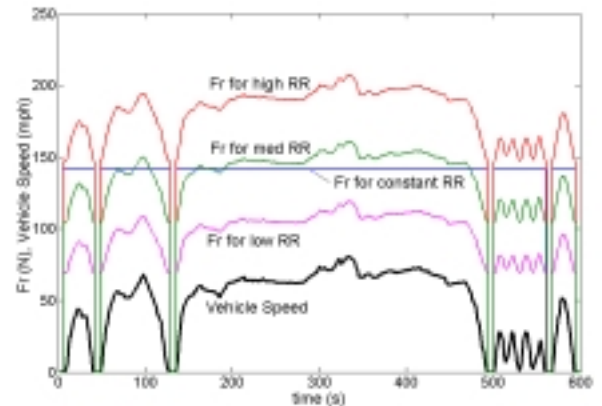


Figure 8. Rolling Force  $F_r$  for US06 cycle

**Table 2. Fuel Economy Results from ADVISOR Simulations**

	Fuel Economy			Percent Change Fuel Economy Compared to MED RR		Return Factor	
	LO RR	MED RR	HI RR	LO RR	HI RR	LO RR	HI RR
<b>Sedan Results</b>						<b>-30.1%</b>	<b>37.9%</b>
FTP	23.1	22.7	22.1	2.1%	-2.5%	7.0%	6.7%
HWFET	40.0	37.8	35.3	5.9%	-6.5%	19.5%	17.2%
US06	26.1	25.2	24.4	3.3%	-3.2%	10.8%	8.6%
<b>SUV Results</b>						<b>-18.8%</b>	<b>7.0%</b>
FTP	17.3	17.0	16.9	1.5%	-1.0%	8.0%	13.6%
HWFET	25.2	24.4	24.0	3.4%	-1.8%	18.1%	25.4%
US06	16.2	15.9	15.7	1.9%	-1.0%	10.2%	14.1%

Shaded cells show percent difference in  $F_{r50}$  compared to MED RR tire

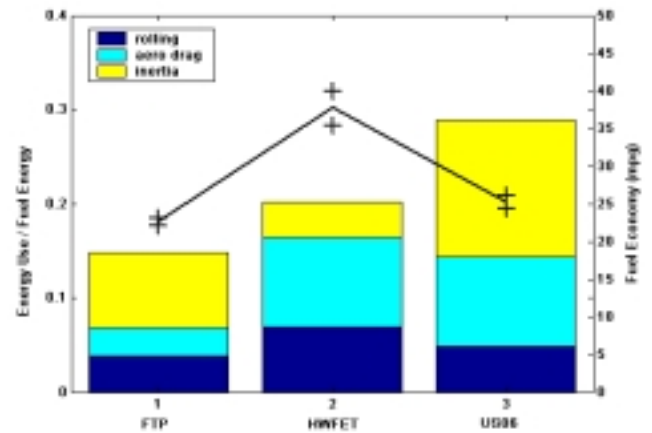
The fuel economy results are summarized in table 2. For these simulations, the new rolling resistance model was used with three different sets of tire data representing high, medium, and low rolling resistance values. The tire rolling resistance data used for this study was provided by Michelin North America, Inc. and is shown in Appendix Table A1. Also shown in the table 2 is the “return factor” (RF) calculated as the ratio of the percent change in fuel economy to the percent change in rolling resistance.

$$RF = \frac{\% \text{ change in fuel economy}}{\% \text{ change in rolling resistance}}$$

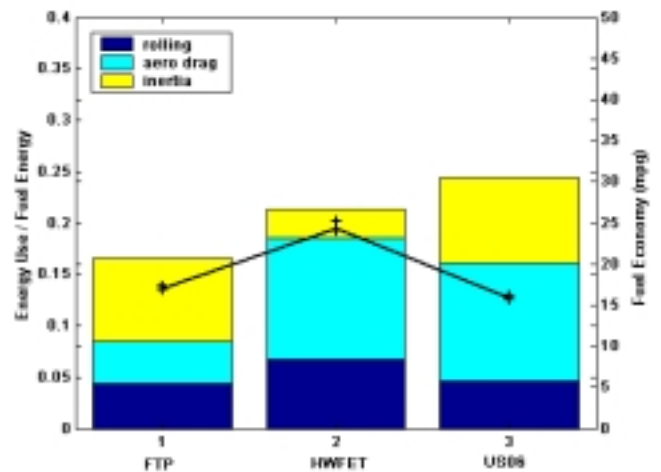
To generate this number, a single rolling resistance force  $F_{r50}$  was calculated at 1000 kg load and a constant rolling force of 50 mph.

For the high and low rolling resistance tires, the percent change in rolling resistance was calculated as the percent change in  $F_{r50}$  compared to the medium tire. These values are shown in Appendix Table A1, and repeated in the shaded cells of table 2 for reference. Using these conditions the calculated return factor for the light duty sedan ranged from 7% for the HI RR tire on the FTP to 19.5% for the LO RR tire on the HWFET cycle. For the SUV, the return factors ranged from 8% for the LO RR tire on the FTP cycle to 25.4% for the HI RR tire on the HWFET cycle. Return factors between 5% and 15% are typical for light duty vehicles<sup>6</sup>. For both vehicles the lowest return factors were seen on the city cycle and the highest return factors were seen on the highway cycle. In other words, the fuel economy benefit/penalty from changing rolling resistance was greatest on the HWFET cycle.

Figures 9 and 10 compare the road load energy expended by a passenger car and SUV respectively for the three different drive cycles.



**Figure 9. Road Load Energy and Fuel Economy Results for Light-Duty Passenger Car**



**Figure 10. Road Load Energy and Fuel Economy Results for Sport Utility Vehicle**

The bars in the figures represent the energy expended to overcome rolling resistance, aerodynamic drag, and inertia expressed as a percentage of total fuel energy input into the vehicle over the cycle. Additionally, the fuel economy is shown on the right-hand “y” axis. The fuel economy for the MED RR tire is shown as a line with the HI RR and LO RR results shown as plus signs above and below the MED RR line. The data for these results is also provided in table A2 of the Appendix.

For the passenger car, we see that the energy required to overcome rolling resistance is 3.9% of the input fuel energy for the city cycle, 6.9% on the highway cycle and 4.9% on the aggressive US06 cycle. Similarly, for the SUV the energy expended for rolling resistance was 4.4% of fuel input energy on the city cycle, 6.7% on the highway, and 4.6% on the US06 cycle. These figures also show that the force required to overcome the vehicle inertia is highest for the FTP and US06 cycles where there are more starts and stops, and that aerodynamic drag is highest on the HWFET and US06 cycles that include higher speeds than the FTP. The spread in fuel economy due to the range of rolling resistance modeled is greatest on the highway cycle. Note that the range in fuel economy is lower for the SUV since the range in rolling resistance values was lower. These values are based on actual tire test data provide by Michelin for existing production tires.

## CONCLUSION

The Department of Energy and its National Renewable Energy Laboratory have developed two important modeling tools that are available for use by industry. DOE’s VISION model uses historical data and projections of population and growth in annual gross domestic product to project highway fuel use to the year 2050. This model can be modified to study various fuel use scenarios. For this paper, the baseline scenario was compared to the case of achieving 2.5% improvement in fleet fuel economy through improvements in rolling resistance and improved tire pressure maintenance. The model showed that energy savings of 3.8 billion gallons per year would be realized from this level of fuel economy improvement to the existing fleet.

The latest release of NREL’s Advanced Vehicle Simulator (ADVISOR 2002) includes an improved rolling resistance model based on SAE J2452 test results. In this paper, some of the capabilities of the tool are demonstrated by simulating the performance of a light

duty passenger car and sport utility vehicle over three different driving cycles. The force due to rolling resistance was compared for the two vehicles using low, medium, and high rolling resistance tire data. The energy expended for rolling resistance, aerodynamic drag, and inertia was compared for the two vehicles and three drive cycles. Using industry-supplied tire rolling resistance data from existing production tires, the ADVISOR simulations showed fuel economy between 2% and 6.5% lower for a light duty passenger car equipped with lower rolling resistance tires, and between 1.0% and 3.4% for a sport utility vehicle over the three different drive cycles.

## ACKNOWLEDGMENTS

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## APPENDIX

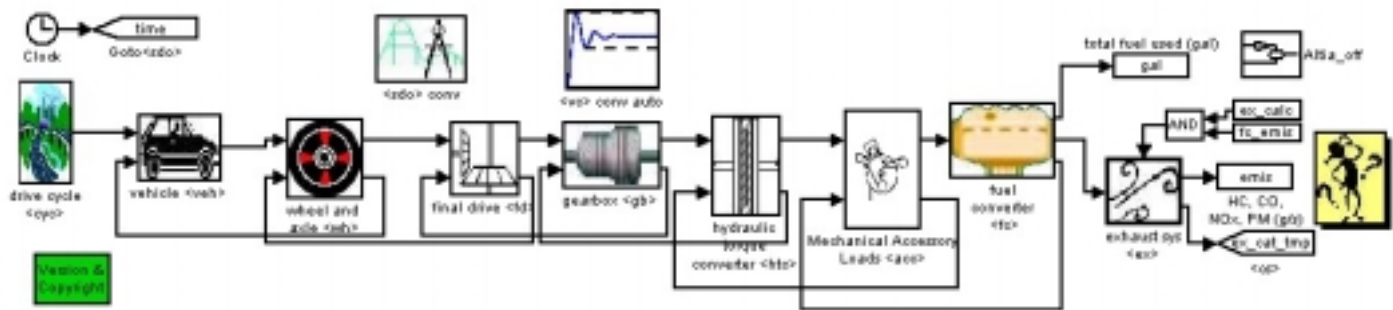


Figure A1. ADVISOR Top-level Block Diagram for Conventional Vehicle Model

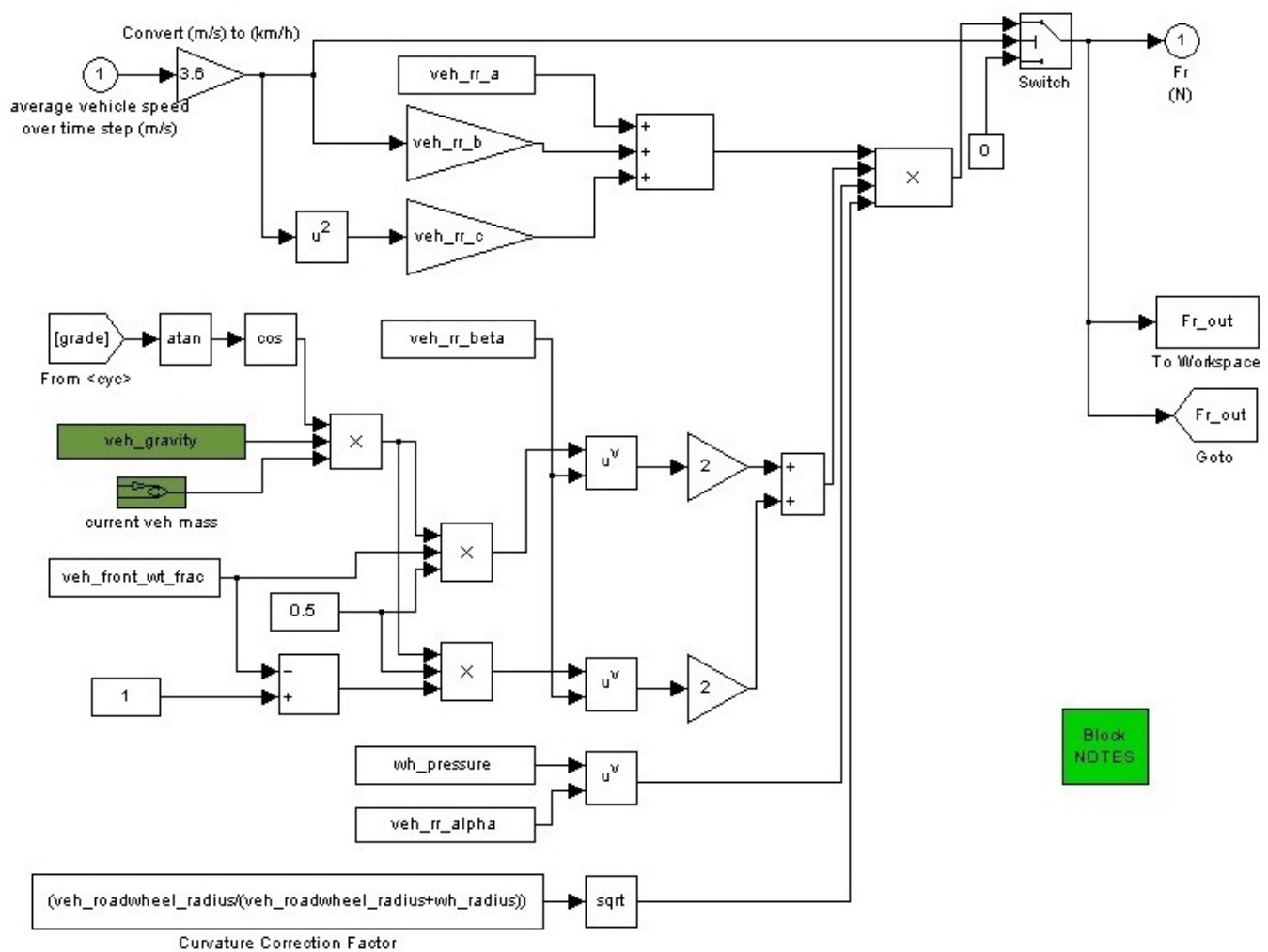


Figure A2. ADVISOR Block Diagram for Calculating Rolling Resistance Force with the Vehicle Block Diagram

**Table A1. Input Tire Rolling Resistance Data**

Tire Size	RR Category	Rolling Resistance Equation Coefficients						
		F <sub>r</sub> per 1000 kg at 50 mph	Difference from MED	alpha	beta	a	b	c
P205/60R15	LO	56.6	-30.1%	-0.4815	1.0051	6.82E-02	2.32E-04	1.20E-06
P205/60R15	MED	80.9	-	-0.4745	0.9552	1.50E-01	4.87E-04	1.18E-06
P205/60R15	HI	111.6	37.9%	-0.4243	0.9568	1.59E-01	3.44E-04	1.25E-06
P235/75R15	LO	73.1	-18.8%	-0.5007	0.9141	2.55E-01	4.69E-04	3.49E-06
P235/75R15	MED	90.1	-	-0.4797	0.9464	2.08E-01	2.56E-04	3.94E-06
P235/75R15	HI	96.4	7.0%	-0.2601	0.8275	2.00E-01	2.50E-05	4.18E-06

**Table A2. Road Load Energy and Fuel Economy Results**

	Energy Summary (kJ)					Fuel Economy		
	Aerodynamic Drag	rolling resistance	inertia	fuel input	engine output	LO RR	MED RR	HI RR
Sedan Results								
FTP	1668.9	2211.2	4580.0	57028.7	10749.8	23.1	22.7	22.1
HWFET	3134.8	2253.6	1226.4	32765.4	7974.8	40.0	37.8	35.3
US06	3624.4	1859.4	5523.3	38129.4	9979.8	26.1	25.2	24.4
SUV Results								
FTP	3190.2	3361.8	6151.0	76751.2	14195.8	17.3	17.0	16.9
HWFET	5995.1	3396.6	1435.4	50753.7	12123.6	25.2	24.4	24.0
US06	6960.5	2825.5	5068.6	60797.4	14846.4	16.2	15.9	15.7